HIGH-SPEED OPTICAL CAMERA COMMUNICATION USING AN OPTIMALLY MODULATED SIGNAL

Masanori Sugimoto
(Hokkaido University, Japan, sugi@ist.hokudai.ac.jp)

Hayato Kumaki
(Hokkaido University, Japan, h.kumaki@frontier.hokudai.ac.jp)

Takayuki Akiyama
(SOKENDAI, Japan, tak@nii.ac.jp)

Hiromichi Hashizume
(National Institute of Informatics, Japan, has@nii.ac.jp)

Overview and Contribution:

- An optical camera communication (OCC) technique using an LED and an off-the-shelf rolling-shutter camera.
- Symbols are encoded as time delays of optimally modulated signals (phase-shift modulation).
- Received symbols are decoded by using intensities obtained from four consecutive line sensors of a camera.
- The proposed technique **achieves 0.833 - 1.17 bits per line (bpl)** and **allows longer exposure time settings** (difficult for existing on-off keying OCC techniques [1,2] as they cannot exceed 1 bpl in principle).

Optimally Modulated Signal for Time Difference Estimation [3]

T_C : camera frame period, $\eta = T_E / T_C$: exposure time ratio, L : number of line sensors,
mT_C: period of transmitted signal $s(t)$ from LED
$\delta m T_C$: time difference between $s(t)$ and camera frame $(0 \le \delta < 1)$ (see Fig. 1)
τ_l : time delay of line sensor l from $s(t)$ $\left(\tau_l = \delta m T_C + \frac{l}{L} T_C,\ l = 0, 1, \ldots, L-1\right)$

Intensity at line sensor l : $r(\tau_l) = \frac{1}{T_C}\int_0^{\eta T_C} s(t + \delta m T_C + \frac{l}{L}T_C)dt = \frac{1}{T_C}\int_0^{\eta T_C} s(t+\tau_l)dt$

Its Fourier transform on δ:

$$R_k(l) = \int_0^1 r(\tau_l)\, dt\, e^{-j2\pi k\delta} d\delta = S_k \eta e^{j\frac{\pi k \eta}{m}} \mathrm{sinc}\left(\frac{\pi k \eta}{m}\right) e^{j\frac{2\pi k l}{mL}} = S_k E_k(l) \quad (S_k : \text{Fourier transform of } s(t))$$

Intensity difference functions (Fig. 2 (b)):

$$r_{d1}(\tau_l) = r(\tau_l) - r(\tau_{l-2}),\ r_{d2}(\tau_l) = r(\tau_{l-1}) - r(\tau_{l-3})$$

Intensity ratio function (Fig. 2 (a)):

$$g(\tau_l) = \begin{cases} \dfrac{r_{d2}(\tau_l)}{2\,(r_{d1}(\tau_l) + r_{d2}(\tau_l))} & (r_{d1}(\tau_l)\, r_{d2}(\tau_l) \ge 0) \\ \dfrac{r_{d1}(\tau_l)}{2\,(r_{d1}(\tau_l) - r_{d2}(\tau_l))} + \dfrac{1}{2} & (r_{d1}(\tau_l)\, r_{d2}(\tau_l) < 0) \end{cases}$$

Triangular wave (Fig. 2 (b),(c)) and its Fourier transform: $F_k(l) = \dfrac{\mathrm{sinc}^2(\frac{k\pi}{2})}{2} e^{\frac{jk\pi}{2}l}$

Optimally modulated signal derived when $R_k(l) = F_k(l)$ holds (Fig. 3) :

$$s_{opt}(t) = \sum_{k=-\infty}^{\infty} \frac{F_k(l)}{E_k(l)} e^{j\frac{2k\pi}{mT_C}t} = \sum_{k=-\infty}^{\infty} \frac{1}{\eta} e^{-j\frac{k\pi\eta}{m}} \frac{\mathrm{sinc}^2(\frac{k\pi}{2})}{\mathrm{sinc}(\frac{k\pi\eta}{m})} e^{j\frac{\pi k l}{2}(1-\frac{4}{mL})} e^{j\frac{2k\pi}{mT_C}t}$$

$m = \dfrac{4}{L} \rightarrow$ irrespective of the value of l, $\eta = \dfrac{m}{2p} = \dfrac{2}{pL}$ $(p = 1, 2, \cdots) \rightarrow S_k \neq 0$ and $S_k \neq \infty$

$$s_{opt}(t) = \begin{cases} 1 - \dfrac{\eta L}{2}\left[\dfrac{t - 4nT_C/L}{\eta T_C}\right] & \left(\dfrac{4nT_C}{L} \le t < \dfrac{(4n+2)T_C}{L}\right) \\ \dfrac{\eta L}{2}\left[\dfrac{t - (4n+2)T_C/L}{\eta T_C}\right] & \left(\dfrac{(4n+2)T_C}{L} \le t < \dfrac{4(n+1)T_C}{L}\right) \end{cases}$$

Time difference estimation at a receiver (Fig. 2(a),(b)):

$$\tau_l = \begin{cases} (2\,T_C/L)\ g(\tau_l) & ((r_{d2}(\tau_l) = 0 \text{ and } r_{d1}(\tau_l) > 0) \text{ or } r_{d2}(\tau_l) > 0) \\ (2\,T_C/L)\ (1 + g(\tau_l)) & ((r_{d2}(\tau_l) = 0 \text{ and } r_{d1}(\tau_l) < 0) \text{ or } r_{d2}(\tau_l) < 0) \end{cases}$$

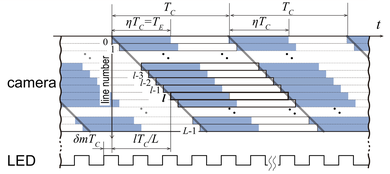

Fig. 1. Exposure timings of line sensors in a rolling-shutter camera.

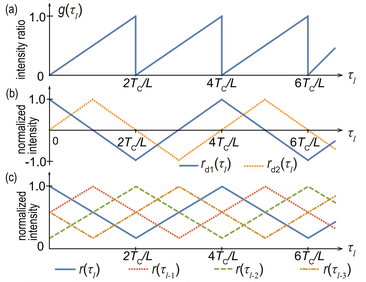

Fig. 2. (a) Intensity ratio function; (b) Intensity difference functions; (c) Intensity functions.

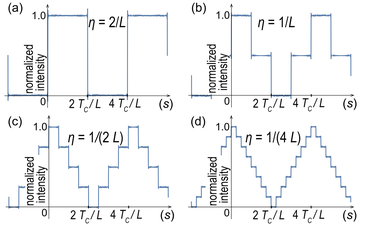

Fig. 3. Optimally modulated signals $s_{opt}(t)$: (a) $\eta = 2/L$, (b) $\eta = 1/L$, (c) $\eta = 1/(2L)$, and (d) $\eta = 1/(4L)$.

Encoding and Decoding

Time delay for an N-bit integer symbol k encoded at a transmitter (Fig. 4): $t_k = \dfrac{2T_C}{L}\left(\dfrac{k}{2^{N-1}} + \dfrac{1}{2^N}\right)$

Decoded symbol k'' from t_k'' at a receiver is given using t_D and t_k' estimated through the time difference estimation and data encoding parts of transmitted signals, respecitively (Fig. 5)

$$\frac{k''}{2^{N-1}} - \frac{1}{2^N} \le \frac{t_k''}{\frac{2}{L}T_C} < \frac{k''}{2^{N-1}} + \frac{1}{2^N} \qquad t_k'' = \begin{cases} t_k' - \tau_l & (t_k' - \tau_l \ge 0) \\ t_k' - \tau_l + \dfrac{4T_C}{L} & (t_k' - \tau_l < 0) \end{cases}$$

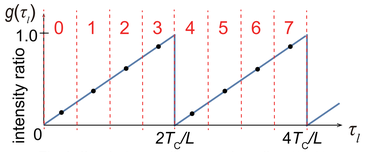

Fig 4. Symbol encoding and decoding (N=3)

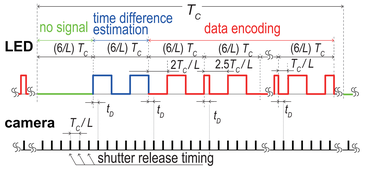

Fig. 5. Configuration of transmitted signal.

Exposure Time Ratio and Communication Speed

For avoiding interferences between symbols, their transmission duration lasts $(4+a)$ T_C/L $(a=1,2,..)$, which needs $(4+a)$ line sensors for decoding. Larger exposure time ratios are allowed under the following condition (Fig. 6) and their communcation speeds are shown in Fig. 7: $\eta = \dfrac{2}{pL}, 1 > \eta \ge \dfrac{4+a}{L} + \dfrac{2}{pL}$

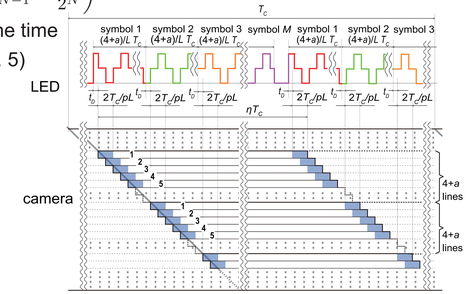

Fig. 6. Symbol transmission and reception for $1 > \eta \ge (4+a)/L + 2/(pL)$.

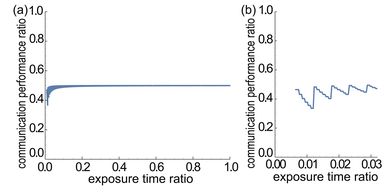

Fig. 7. Ratio of transmission speeds comparing those of the $1 > \eta \ge (4+a)/L + 2/(pL)$ case with those of the $\eta = 2/(pL)$ case ($a = 2$, $p = 2$). (a) $\eta < 1$. (b) magnified view of (a) ($\eta < 3.24 \times 10^{-2}$).

Performance Evaluation

The performance of the proposed technique (Fig. 8) was confirmed through three expeirments as shown in Tab. 1.

Parameter	Experiment 1	Experiment 2	Experiment 3
Exposure time ratio η	1.91×10^{-3}	1.91×10^{-3}	3.24×10^{-2} 1.01×10^{-1}
Measurement environment I_B	"dark" , "fluo"	"dark"	"dark" , "fluo"
Distance d (m)	0.03	0.03, 0.5, 1.0, 1.5	0.03
Number of pixels P_N	100, 300, 600, 1324	40	40
Bits per symbol N	6, 7, 8, 9, 10	6, 7, 8, 9, 10	3, 4, 5, 6, 7
Number of measurements	40,000 (=1,000×5×4×2)	40,000 (=2,000×5×4)	40,000 (= 2,000×5×2×2)

Tab. 1. Experimental parameters and their values
("dark" : no illumination, "fluo" : fluorescent illumination).

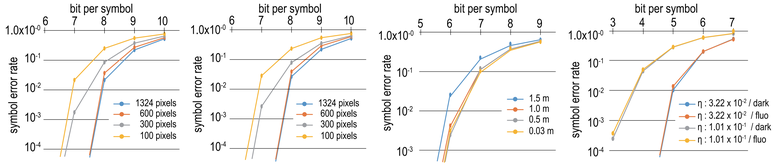

Fig. 8. Symbol error rates: (a) different numbers of pixels per line sensor in a dark environment; (b) different numbers of pixels per line sensor under fluorescent light; (c) different distances; and (d) different exposure time ratios.

Conclusion and Future Work

- A High-speed OCC technique was proposed.
- More intensive experiment and evaluation will be conducted.
- Smartphone applications (e.g. AR) will be implemented.

REFERENCE

[1] H. Aoyama and M. Oshima, "Visible Light Communication Using a Conventional Image Sensor," in *Proceedings of IEEE CCNC 2015*, Las Vegas, NV, 2015, DOI: 10.1109/CCNC.2015.7157954.

[2] C. Danakis, M. Afgani, G. Povey, I. Underwood, and H. Haas, "Using a CMOS Camera Sensor for Visible Light Communication," in *Proceedings of IEEE GLOBECOM 2012*, Anaheim, CA, 2012, pp. 1244–1248.

[3] M. Sugimoto, M., H. Kumaki, T. Akiyama, H. Hashizume: Optimally Modulated Illumination for Rapid and Accurate Time Synchronization, *IEEE Transactions on Signal Processing*, Vol.65, No.2, pp.505-516 (2017).

Intelligent Information Systems Laboratory, Graduate School of Information Science and Technology, Hokkaido University
http://aiwww.main.ist.hokudai.ac.jp/